Final Report

Evanescent Field Imaging of Novel Optical Waveguide Structures: An Ultra-High Spatial Resolution Probe of Topographic, Dielectric, and Spectroscopic Properties

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ARO Grant #DAAL03-92-G-0245

Under this grant we have carried out a research program utilizing near field optical microscopy (NSOM) to investigate spatial configurations of both integrated photonic structures and semiconductor nanostructures. Near field techniques have become attractive for optical characterization because by probing the near field the diffraction limit of conventional microscopy can be overcome. Spatial resolutions much smaller that the optical wavelength (λ) can be obtained, approaching $\lambda/50$. In the grant we have custom-built an NSOM instrument and reported the first results on the use of near field techniques to measure and image (1) the transverse field across an optical channel waveguide, (2) the evolution of the transverse field variation as light propagates through the integrated optic structures of a directional coupler and a y-junction, and, (3) very recently (accepted for publication), have accomplished the extension of these

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13. ABSTRACT *(Maximum 200 words)*

Under this grant we have carried out a research program utilizing near field optical microscopy (NSOM) to investigate spatial configurations of both integrated photonic structures and semiconductor nanostructures. Near field techniques have become attractive for optical characterization because by probing the near field the diffraction limit of conventional microscopy can be overcome. Spatial resolutions much smaller that the optical wavelength (λ) can be obtained, approaching $\lambda/50$. In the grant we have custom-built an NSOM instrument and reported the first results on the use of near field techniques to measure and image (1) the transverse field across an optical channel waveguide, (2) the evolution of the transverse field variation as light propagates through the integrated optic structures of a directional coupler and a y-junction, and, (3) very recently, have accomplished the extension of these near field techniques to the study of field distributions in semiconductor waveguide structures where to model our experimental results the use of the beam propagation method is required.

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Near field optics, optical channel waveguide; directional coupler; y branch semiconductor waveguide; beam propagation method.

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near field techniques to the study of field distributions in semiconductor waveguide structures.

Although not listed in our original proposal as cost sharing, we have obtained considerable additional support for this grant. In support of the research performed under this grant we have received significant equipment funding to enhance our near field laboratory capability from the NSF Infrastructure Program and the Ohio Research Challenge Program. We have slso had a related ASSERT program and other related grant support.

We briefly review these accomplishments below, including the theoretical context as well as providing a list of presentations, publications, theses, and dissertations that have resulted from this grant. More details of the results, as well as details of the fabrication and experimental conditions, can be found in these publications.

(1) Use of NSOM to Characterize Optical Waveguide Structures

We have reported the use of the NSOM to probe the exponentially decaying evanescent field to obtain measurements of the local effective refractive index in optical waveguide structures. We have demonstrated the use of both a tapered optical fiber probe to measure the effective refractive index in a Si_3N_4/SiO_2 dielectric optical channel waveguides, in which the channel is formed by a partially etched ridge structure.

Optical channel waveguides were fabricated using a ridge structure and were designed (see Fig. 1) so that each of the channel waveguides

supported waveguide propagation of a single mode at a He-Ne laser wavelength of 632.8 nm and a semiconductor laser diode wavelength of 830 nm. To probe these waveguides, we used a conventional NSOM arrangement with the addition of an infrared camera system to facilitate coupling at 830 nm and positioning the fiber tip over the channel waveguide. For most of these initial measurements we employed an uncoated multimode fiber tip; present practice employs a tapered single mode tip coated with aluminum except at the very tip.

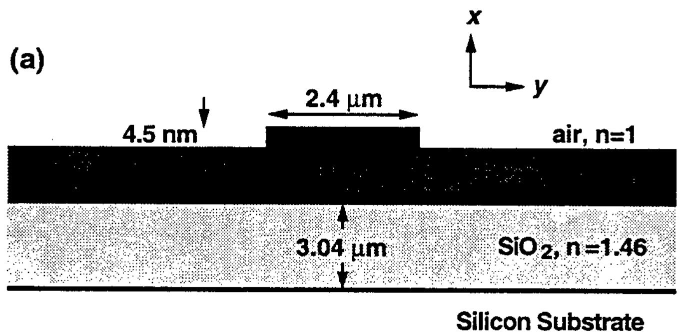

Figure 1: A single mode ridge channel waveguide fabricated on a silicon substrate.

These initial NSOM measurem ents of evanescent field intensity versus distance from the waveguide surface show the expected exponential variation, The exponential decay length values agree extremely well with values from modeling calculations. Recent examples of model calculations are briefly discussed in section 3 below. Results of a transverse scan of the evanescent fields obtained using both 633 nm and 830 nm excitation (the date which are displayed on a log scale in the Fig. 2) show the expected cosine squared behavior over the waveguide ridge, and an exponentially decaying behavior as one moves away from the ridge.

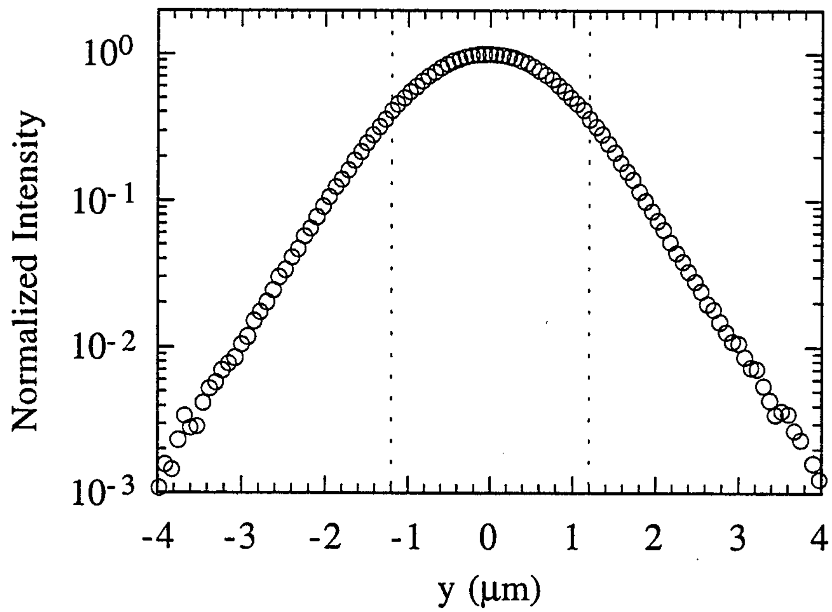

Figure 2: A semilog plot of near field intensity versus transverse distance across the single mode waveguide. Note the cosine squared dependence in the central channel region (between the dotted lines) and the exponential fall off (straight lines) outside the channel region.

These initial measurements established the NSOM technique as capable of characterizing the local effective index of optical waveguide structures in a variety of circumstances.

(2) NSOM Characterization of Directional Couplers and Y-branches

We have used the NSOM to investigate the field intensity distributions in phase-matched directional couplers and Y-branches. These structures have been studied in detail; they represent the infrastructure of every optoelectronic integrated circuit (OEIC) and photonic integrated circuit (PIC). We provided the first demonstration of the use of the NSOM to probe these structures on a local

scale. We first discuss measurements of a directional coupler, followed by some brief results obtained from Y-branch structures.

The directional coupler incorporated strip-loaded single mode waveguides, each consisting of a lower cladding layer of SiO_2, a Si_3N_4 core, and a SiO_2 loading strip, were fabricated by LPCVD (see Fig. 3). A continuous change of mode intensity (see Fig. 4), indicating optical power transfer, was measured in the near field above the two waveguides of the directional coupler as the light propagated through it. We also display in Fig. 4-b a graph of our results where the intensity in each waveguide is plotted versus distance along the directional coupler. The measurements provide a real space picture of the spatial evolution of the optical power transfer and can be compared to detailed model calculations. Figure 4-b is a plot of the intensities (circles) along each branch of the directional coupler along with a model calculation using the beam propagation method (solid lines).

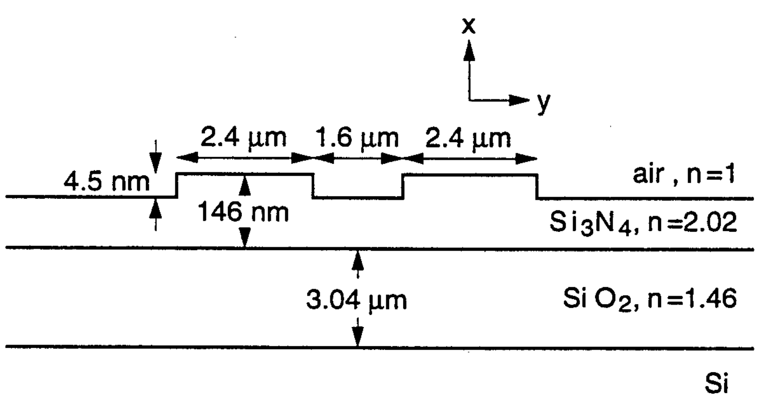

Figure 3: Two single mode channel ridge waveguides separated by 1.6 μm, a directional coupler structure.

Agreement with the modeling calculation displayed in Fig. 4b is excellent.

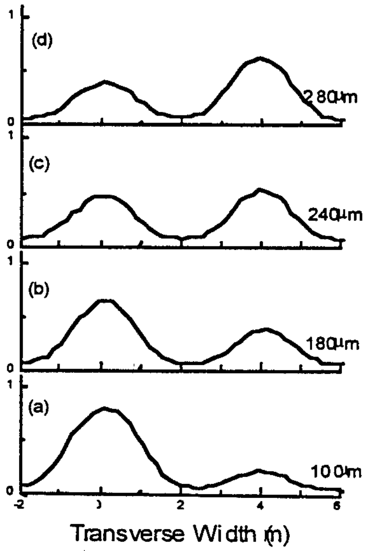

Figure 4a: The evolution of near field intensity along a directional coupler. Channel waveguides are centered at 0 and 4 µm. As the distance increases, note the increase in intensity in one waveguide and the decrease in the other.

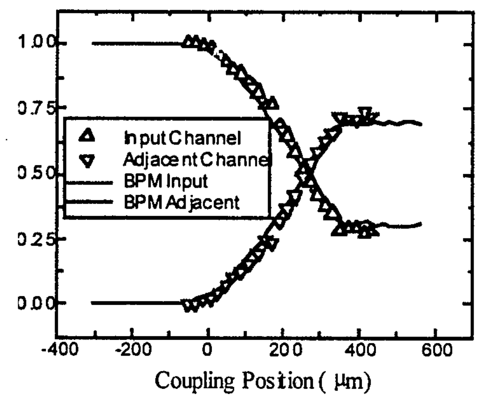

Figure 4b: Measured near field intensity versus distance along the directional coupler (triangles) and beam propagation (BPM) calculations (solid lines).

Next we show results obtained from a Y-branch structure in Fig. 5 below.

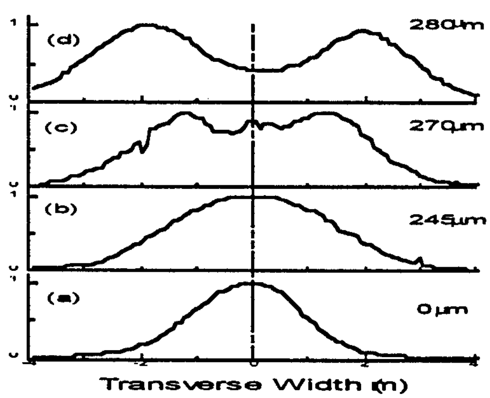

Figure 5: NSOM data versus distance across a Y-branch structure, near the point of branching. Note the appearance of two distinct peaks by 250µm.

This NSOM data was obtained for a Y-branch consisting of a 2.4 μm wide waveguide branching into two 2.4 μm wide waveguides with an angle of 2° between them. We can clearly observe in Fig. 5 the splitting of the waveguide and, although the structure was designed symmetrically, the asymmetric power splitting. An understanding of these results should allow the design and fabrication of more efficient or more appropriate Y-branch (as well as other integrated optic) structures.

(3) Semiconductor waveguide structures

Very recently (accepted for publication), we have accomplished the extension of these near field techniques to the study of field distributions in semiconductor waveguide structures. NSOM measurements of the channel waveguide intensity distribution are significantly more difficult for semiconductor channel waveguides than for low index channels since the field in a semiconductor waveguide is much more tightly confined due to the larger refractive index difference between the guiding layer and the upper cladding layer of air. For waveguides that we have examined, for example, the evanescent field intensity at the surface of a semiconductor waveguide is 25 times smaller than that of a low index waveguide with a similar structure. In addition, the intensity decays more rapidly away from the surface of a semiconductor waveguide than that of a low index waveguide, with decay lengths typically of 20 nm and 50 nm, respectively.

The channel waveguide structure we studied is shown in the Fig. 6. The channel waveguide is formed by etching a ridge in the $Al_{0.1}Ga_{0.9}As$

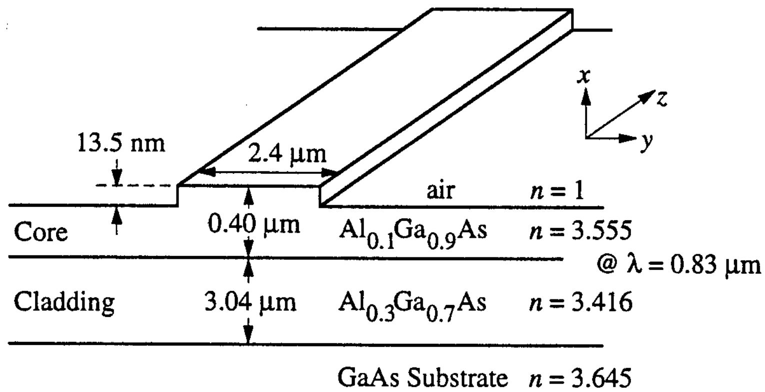

Figure 6: Schematic diagram of the AlGaAs heterostructure single mode channel waveguide. Nominal values of aluminum concentration and refractive index are indicated.

waveguide layer which is epitaxially grown on a lower cladding layer of $Al_{0.3}Ga_{0.7}As$. The ridge height of 13.5 nm and channel waveguide width of 2.4 µm, measured separately using atomic force microscopy, allow single mode propagation for an excitation wavelength of 830 nm.

Two methods were used to model the field profile of the quasi-TE_0 mode in this waveguide; the effective index method (EIM) and the beam propagation method (BPM). The effective index method can be used to model the two dimensional channel mode field profile by considering the field to be a separable function of x and y, $E(x,y) = E(x)E(y)$. We assume $E(x)$ to be the same field as the TE field calculated for the three layer planar waveguide which would be formed by making the ridge infinitely wide. The resultant effective index we denote as n_{e2}. We also compute the TE effective index n_{e1} of the three layer planar

waveguide which would be formed by making the ridge width zero. $E(y)$ is taken to be the TM field calculated for the symmetric three layer planar waveguide which has a core index n_{e2} and cladding index n_{e1} and has a thickness equal to the width of the ridge. The intensity profile is proportional to the square of the field profile. Therefore, for a channel with core thickness t and width w and with the (0,0) position located in the center of the ridge at the core-cladding interface, the intensity profile above the waveguide surface for the quasi-TE$_0$ mode is given by;

$$I(x,y) = A\cos^2(k_y y)\exp\left(\frac{-x}{\zeta_{1x}}\right) \qquad |y| \le w,\ x \ge t$$

$$I(x,y) = B\exp\left(\frac{-|y|}{\zeta_y}\right)\exp\left(\frac{-x}{\zeta_{1x}}\right) \qquad |y| \ge w,\ x \ge t$$

$$I(x,y) = C\exp\left(\frac{-|y|}{\zeta_y}\right)\cos^2(k_x x + \phi) \qquad |y| \ge w,\ x \le t$$

where

$$k_y = k_0\sqrt{n_{e2}^2 - n_{\text{net}}^2} \qquad k_x = k_0\sqrt{n_{\text{core}}^2 - n_{e2}^2}$$

$$\zeta_y = \frac{2}{k_0\sqrt{n_{\text{net}}^2 - n_{e1}^2}} \qquad \zeta_{1x} = \frac{2}{k_0\sqrt{n_{e2}^2 - 1}}$$

$k_0 = 2\pi/\lambda$, and A, B, C, and ϕ, are constants. Thus within the EIM model the intensity varies as cosine squared over the ridge and decreases exponentially away from the ridge.

The beam propagation method is a more accurate, but computationally more intensive, way for determining the field distribution in a channel waveguide. BPM is able to properly account for ridge topography because it

considers the actual variation of refractive index of the waveguide cross section as a function of x and y.

Near field scanning optical microscopy (NSOM) measurements on the single mode channel waveguide structure of Fig. 6 were carried out by endfire coupling light of 830 nm from a semiconductor diode laser into the channel waveguide to excite the TE_0 mode. Near field measurements, performed in the usual manner, are plotted in Fig. 7, along with NSOM curves calculated from the EIM and BPM mode profile models.

There is general qualitative agreement between the actual data and the simulations. A noticeable asymmetry exists between the intensities measured on either side of the waveguide which may be related to a local asymmetry in the cross section of the ridge. The measured data above the ridge region were fit to $\cos^2(k_y y)$ giving a propagation constant k_y of 0.97 rad/μm^{-1}. This value is somewhat greater than the value of 0.73 rad/μm^{-1} calculated by the models, which both predict the same cosine squared variation of intensity except near the ridge edges. Exponential fits to the measured data

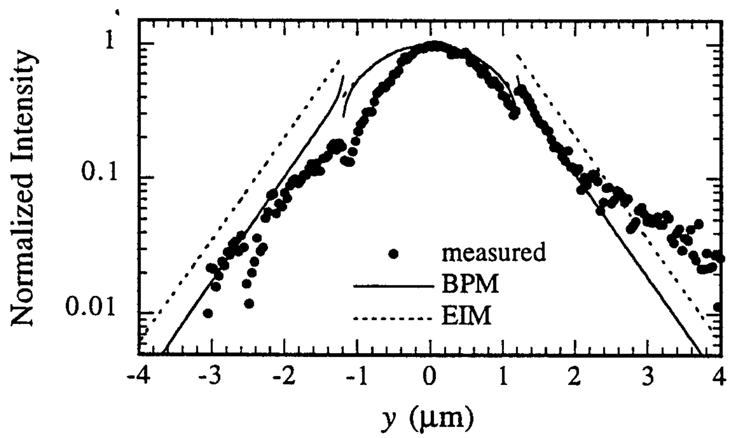

Figure 7: Near field intensity measurements versus distance across the single mode channel waveguide. Calculations are displayed for the effective index model (EIM, dashed lines) and the beam propagation method (BPM, solid lines).

outside the ridge gave decay constants z_y of 740 ± 65 nm and 700 ± 165 nm to the left and right of the ridge, respectively, which are larger than those calculated by the BPM and EIM. A ±3% uncertainty in the nominal aluminum concentrations in the waveguide samples would account for this difference.

Of great interest are the sharp features seen in the data at the ridge edges. Although both the EIM and the BPM predict somewhat similar features, which are a result of the optical intensity distribution for this waveguide and the probe tip following the surface topography, the shape and magnitude are *significantly better* approximated by the BPM calculations. This is directly attributable to the use, by the BPM, of the actual material index as a function of position and is reflected in the way the BPM intensity contours follow the ridge topography. Away from the ridge, the decay lengths predicted by both models are approximately equal as indicated by the parallel curves. However, the BPM simulation again follows the data more closely than the EIM simulation and has a significantly smaller magnitude (by a factor of 2) than that predicted by the EIM. The ability to accurately predict this magnitude is critical when designing devices which utilize waveguide field interaction, for instance directional couplers.

Summary

In summary, NSOM measurements of optical intensity distributions of integrated photonic structures and semiconductor nanostructures has been underway. As a part of this grant, our group has been the first one to perform

measurements of planar waveguide decay lengths, channel waveguide mode intensity distributions, optical intensity distributions in directional couplers and Y-junctions, and channel waveguide mode intensity distributions in compound semiconductor channel waveguides. Modeling has been performed to assess how well the measurements agree with theoretical calculations. The NSOM measurements were more difficult for the compound semiconductor waveguides because the high refractive index causes the field to have a lower value at the surface and to decay much faster away from the surface. Our measurements utilizing a compound semiconductor waveguide have been carried out on single mode AlGaAs ridge channel waveguides. Sharp features in the intensity measured near the ridge edges are a consequence of the waveguide topography, the high refractive index of the semiconductor material, the resulting strong confinement of the field, and the constant height near field measurement. These measurements have been compared to simulations calculated using the effective index method and the beam propagation method. We have shown that to accurately model the measured sharp intensity features and the magnitude of the intensity outside the channel region, the beam propagation method must be used.

List of Publications resulting from this grant:

Publications

Journal Papers

C.D. Poweleit, D.H. Naghski, S.M. Lindsay, J.T. Boyd, and H.E. Jackson, "Near Field Scanning Optical Measurements of Optical Intensity Distributions in Semiconductor Channel Waveguides," Applied Physics Letters, accepted for publication (1996).

H.E. Jackson, S.M. Lindsay, C.D. Poweleit, D.H. Naghski, G.N. De Brabander, and J.T. Boyd, "Near Field Measurements of Optical Channel Waveguide Structures," Ultramicroscopy, Vol. 61, pp. 295-298, 1995.

M.H. Chudgar, A.G. Choo, H.E. Jackson, G.N. De Brabander, M. Kumar, and J.T. Boyd "Photon Scanning Tunneling Microscopy of Optical Channel Waveguides" Ultramicroscopy, Vol. 58, pp. 12-17, February, 1995.

A.G. Choo, H.E. Jackson, U. Thiel, G.N. De Brabander, and J.T. Boyd, "Near Field Measurement of Optical Channel Waveguides and Directional Couplers," Applied Physics Letters, Vol. 65, pp. 947-949, August 22, 1994.

H.E. Jackson and J.T. Boyd, "Raman and Photon Scanning Tunneling Microscopy of Optical Waveguides," Optical and Quantum Electronics, Vol. 23, pp. S901-S907, 1991.

Conference Presentations With Published Proceedings

D.H. Naghski, S.M. Lindsay, C.D. Poweleit, J.T. Boyd, and H.E. Jackson, "Near Field Scanning Optical Microscopy of Semiconductor Channel Waveguide Optical Intensity Distributions," presented at and to be published in the proceedings of the 23rd International Conference on the Physics of Semiconductors (ICPS-23), Berlin, Germany, July, 1996.

D.H. Naghski, S.M. Lindsay, C.D. Poweleit, G.N. De Brabander, V. Subramaniam, H.E. Jackson, and J.T. Boyd, "Use of Near Field Scanning Optical Microscopy (NSOM) to Characterize Optical Channel Waveguide Structures," presented at and to be published in the proceedings of the SPIE Photonics West Meeting, Jan., 1996.

H.E. Jackson, S.M. Lindsay, C.D. Poweleit, D.H. Naghski, G.N. De Brabander, and J.T. Boyd, "Near Field Measurements of Optical Channel Waveguide Structures," presented at and to be published in the proceedings of the Third

International Conference on Near Field Optics, Prague, Czechloslovokia, May, 1995.

S.M. Lindsay, D.H. Naghski, G.N. De Brabander, J.T. Boyd, and H.E. Jackson, "Near Field Measurements of Optical Channel Waveguide Structures," presented at and published in the proceedings of the SPIE Meeting, San Diego, CA, July, 1995.

A. G. Choo, U. Thiel, G. DeBrabander, J. T. Boyd, and H. E. Jackson, "Near Field Measurements of Optical Directional Couplers," presented at and published in the proceedings of the SPIE Meeting, San Diego, CA, 1994.

M.H. Chudgar, A.G. Choo, H.E. Jackson, G.N. De Brabander, M. Kumar, and J.T. Boyd "Photon Scanning Tunneling Microscopy of Optical Channel Waveguides" presented at and published in the proceedings of the Second International Conference on Near Field Optics, October, 1993.

A.G. Choo, M.H. Chudgar, H.E. Jackson, G.N. De Brabander, M. Kumar, and J.T. Boyd, "Photon Scanning Tunneling Microscopy of Optical Waveguide Structures" presented at the Materials Research Society Meeting, Dec. 1993 and published in Materials Research Society Symposium Proceedings.

Y. Wang, M. Chudgar, H.E. Jackson, J.S. Miller, G.N. De Brabander, and J.T. Boyd "Characterization of Si_3N_4/SiO_2 Optical Channel Waveguides by Photon Scanning Tunneling Microscopy," presented at and published in the proceedings of the SPIE OE/Fibers Meeting, Boston, MA, 1992.

Conference Presentations with No Published Proceedings

C.D. Poweleit, D.H. Nagaski, S.M. Lindsay, J.T. Boyd, and H.E. Jackson"Near field microscopy of semiconductor waveguides" presented at the Ninth International Conference on Superlattices, Microstructures and Microdevices, Liege, Belgium, July 14, 1996.

C.D. Poweleit, S.M. Lindsay, D.H. Naghski, J.T. Boyd, and H.E. Jackson, "Near Field Microscopy of Modal Variations in Semiconductor Waveguides," presented at the American Physical Society Meeting, March, 1996.

S.M. Lindsay, C.D. Poweleit, D.H. Naghski, G.N. De Brabander, J.T. Boyd, and H.E. Jackson, "Near Field Profiles of Guided Mode Intensity Distributions in Optical Waveguides," presented at the American Physical Society Meeting, March, 1996.

S.M. Lindsay, C.D. Poweleit, D.H. Naghski, G.N. De Brabander, J.T. Boyd, and H.E. Jackson, "Near Field Measurements of Optical Channel Waveguide Structures," presented at the Ohio Sectio Meeting of APS, Fall, 1995.

Y. Wang, J.T. Boyd, and H.E. Jackson, "Photon Scanning Tunneling Microscopy and Waveguide Structures," presented at the Ohio American Physical Society Meeting, April, 1992.

Ph. D. Dissertations

A. G. Choo, "Optical Characterization of Locally and Compositionally Mixed Superlattices using Conventional and Focused Ion Beam Implantation," 1992.

G. N. DeBrabander, "Integrated Optical Interferometers with Micromachined Diaphragms for Pressure Sensing," Ph.D. Dissertation, 1996.

M.S. Theses

M. Chudgar, "Photon Scanning Tunneling Microscopy of Optical Channel Waveguides," 1993.

V. Subramaniam, "Characterization of Field Profile and Loss in Curved Channel Optical Waveguides," M. S. Thesis, 1996.